Evolution of the $\nu = 1$ Ground-State in Coupled Double Quantum Wells: Optical Evidence for Broken-Symmetry States

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(February 1, 2008)

We present the first magneto-absorption studies of coupled electron double layers in the quantum Hall regime. Optical absorption spectra in the vicinity of total filling factor $\nu = 1$ reveal intriguing behavior that have no analog in the single electron layer $\nu = 1$ state and demonstrate the interplay between single-particle tunneling and inter-layer Coulomb effects. The spectra provide direct evidence of a ground-state that evolves from a region dominated by single-particle tunneling to a regime in which inter-layer Coulomb interactions determine the nature of the ground-state. Moreover the spectra provide the first direct evidence that the *incompressible* ground-state at $\nu = 1$ in the many-body regime is not fully pseudospin polarized and is sensitive to the effects of quantum fluctuations in the pseudospin variable.

PACS numbers: 73.20.Dx, 73.20Mf, 78.30.Fs

The fractional quantum Hall effect (FQHE) is understood as arising from a gap in the excitation spectrum of a two-dimensional (2D) electron system caused by strong Coulomb interactions in the presence of a large perpendicular magnetic field sufficient to quench the electronic kinetic energy. Generally, such quantum Hall states can be represented by a single component many-body wavefunction describing the correlated 2D orbital motion of the electrons [1]. An interesting twist to the problem is added when some internal degree of freedom is not frozen out by the magnetic field and persists as a dynamical variable. The spin degree of freedom in the limit of small Zeeman coupling is a prime example of such a *multicomponent* quantum Hall system. The impact of spin for determining the excitation spectrum around filling factor $\nu = 1$ in the single-layer 2D electron system has been an area of recent intense theoretical and experimental inquiry [2–8]. There now exists a large body of evidence that the quantum Hall state at $\nu = 1$ in the single-layer system is more appropriately viewed as a "fractional" state inasmuch as the gap in its excitation spectrum survives the collapse of the single-particle spin gap.

Another multicomponent quantum Hall system occurs in the coupled double quantum well (DQW) structure [9]. By growing two 2D electron layers in close proximity, a new degree of freedom associated with the layer index is introduced. In direct analogy with the spin-1/2 system, the layer index is associated with a double-valued pseudospin variable. An electron in the "upper" layer is in an eigenstate of the pseudospin operator S_z with eigenvalue +1. Similarly an electron in the "lower" layer has eigenvalue -1. In the presence of tunneling, symmetric and anti-symmetric combinations of the eigenstates of S_z can be constructed which are eigenstates of S_x. At B=0, these states are separated by a single-particle tunneling energy gap, Δ_{SAS}. At total filling factor $\nu = 1$, the non-interacting ground-state will consist of a fully populated symmetric state of the spin-up branch of the lowest Landau level (LLL). In the pseudospin picture, this state is fully pseudospin polarized along the $\hat{x}$ direction. Nevertheless, theory has anticipated that inter-layer Coulomb interactions will profoundly alter the nature of the quantum Hall states of the DQW at $\nu = 1$ [10–13]. Indeed, the reduction of symmetry introduced by the inter-layer Coulomb interaction is expected to introduce quantum fluctuations which destroy the full pseudospin polarization of the $\nu = 1$ ground-state [13]. Despite a fluctuating pseudospin polarization, the system remains incompressible and exhibits well-defined quantum Hall state. A non fully pseudospin polarized ground-state concomitant with an excitation gap represents one of the most unusual and non-trivial aspects of inter-layer coherence.

To date, most experimental investigations of coupled double layer quantum Hall systems have been limited to transport studies [9,14,15]. At total filling factor $\nu = 1$, the appearance of incompressible quantum Hall states or compressible ground-states is determined by the delicate balancing of the tunneling gap Δ_{SAS}, the inter-layer Coulomb energy scale set by the distance d between 2D electron layers, and the intra-layer Coulomb correlations determined by l_0, the magnetic length, where $l_0 = (\hbar/eB)^{\frac{1}{2}}$. In seminal work, Murphy *et al.* [14] constructed a phase diagram for $\nu = 1$ in the DQW struc-

ture. In addition to determining a well-defined phase boundary between regimes which support a gapped $\nu = 1$ state and those for which the ground-state at $\nu = 1$ is compressible, they also found that the double layer $\nu = 1$ quantum Hall state evolves continuously from a regime in which the gap is largely determined by single-particle tunneling to a regime where the gap is necessarily of a many-body origin. Their measurements in the weak tunneling regime suggest that the $\nu = 1$ quantum Hall state in the DQW structure also survives the collapse of the single-particle gap. While it is clear that the ground-state must evolve as the tunneling strength is reduced relative to the inter-layer Coulomb interactions, transport cannot clearly distinguish between the two regimes nor directly probe the pseudospin configuration of the ground-state, leaving many intriguing questions open.

In this letter, we present to our knowledge the first magneto-absorption measurements of the coupled DQW system in the quantum Hall regime. Our discussion will focus on total filling factor $\nu = 1$. We have studied a number samples in order to investigate the optical response of the coupled 2D electron system as the sample parameters are tuned from a regime where a gap in the single-particle spectrum accounts for the quantum Hall effect at $\nu = 1$ to a regime where a quantized Hall state at $\nu = 1$ reflects a correlated many-body ground-state. The observed spectra provide direct evidence that the DQW system in the many-body regime exactly at $\nu = 1$ is *not fully pseudospin polarized*. It is important to note that all samples used in this study exhibit well-defined quantum Hall plateaux and longitudinal resistivity minima at $\nu = 1$. While transport shows similar behavior, interestingly, the observed optical spectra display qualitatively different behavior depending on the sample's position on the $\nu = 1$ phase diagram. We suggest that the observed spectral changes reflect an evolution of the ground-state at $\nu = 1$ driven by quantum fluctuations in the pseudospin degree of freedom.

Optical probes provide complimentary means for probing the integral and fractional quantum Hall regimes, but their application to the coupled double electron layer system at $\nu = 1$ has been rather limited. An optical emission study [16] of the DQW structure has observed anomalies at $\nu = 1$ which have been associated with a change in the pseudospin state, but a complete understanding of this emission data is still lacking. Recently, inelastic light scattering has been successfully employed to observe a collapse of collective spin-wave excitations at *even* filling factors in the DQW system [17,18]. Magneto-absorption spectroscopy relies on its ability to discriminate between occupied and unoccupied states in the vicinity of the Fermi level. Absorption can only occur into *unoccupied* states and therefore monitoring absorption into the symmetric and antisymmetric levels as the Fermi level sweeps through $\nu = 1$ may be used to elucidate the ground-state pseudospin configuration.

We discuss in detail absorption spectra obtained from two distinct modulation-doped DQW samples grown by molecular beam epitaxy. Sample A consists of two identical 180$\AA$ GaAs quantum wells separated by a 79$\AA$ $Al_{0.1}Ga_{0.9}As$ undoped barrier layer. The electron density in this sample is $n = 6.3 \times 10^{10}$ cm^{-2} and the mobility is close to 10^6cm^2/Vs at low temperatures. At $B = 0$, $\Delta_{SAS} = 0.7$meV in this sample, as measured by inelastic light scattering [19]. Sample B consists of two identical 180$\AA$ GaAs quantum wells separated by a 31$\AA$ undoped $Al_{0.3}Ga_{0.7}As$ barrier. The density is $n = 1.3 \times 10^{11}$cm^{-2} with a mobility of 10^6cm^2/Vs. The tunneling gap Δ_{SAS} for sample B is 0.4meV. In order to perform transmission studies, the samples are mounted strain-free on Corning glass which has a coefficient of thermal expansion matched to GaAs. The bulk substrate is then removed via a combination of mechanical polishing and a modified chemical jet-etching process [20].

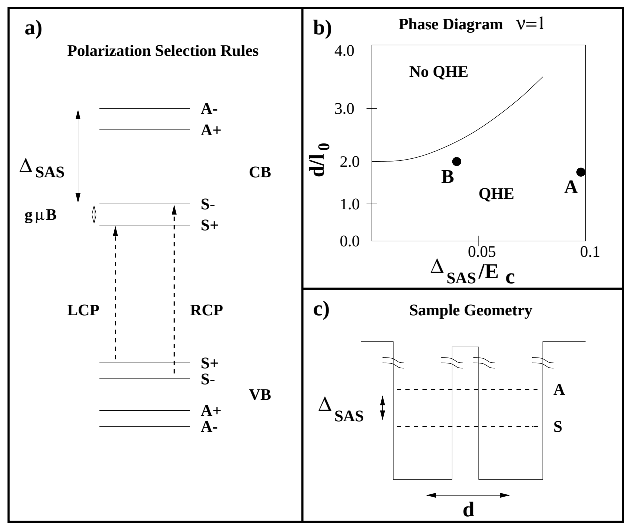

FIG. 1. (a) Schematic representation of polarization selection rules governing inter-band absorption at $\nu = 1$. The dashed lines correspond to the two lowest-energy transitions in the left-circular polarization (LCP) and the right-circular polarization (RCP). (b) Phase diagram of $\nu = 1$ in the DQW structure constructed by Murphy *et al.* [14]. The x axis measures the tunneling gap Δ_{SAS} in units of the basic Coulomb energy $E_c = e^2/\epsilon l_0$. The y axis scale, d/l_0, measures the ratio of intra-layer to inter-layer Coulomb interactions. d is the center-to-center well separation and l_0 is the magnetic length. (c) Schematic of DQW structure used in these studies with the symmetric-antisymmetric gap, Δ_{SAS}, displayed.

Accessible temperatures were in the range of $0.5K \leq T \leq 4.2K$. The measured absorption coefficient is given as $\alpha = -1/L_w ln[I(B)/I(0)]$, where L_w is the quantum

well width, I the measured transmission intensity, and B the magnetic field.

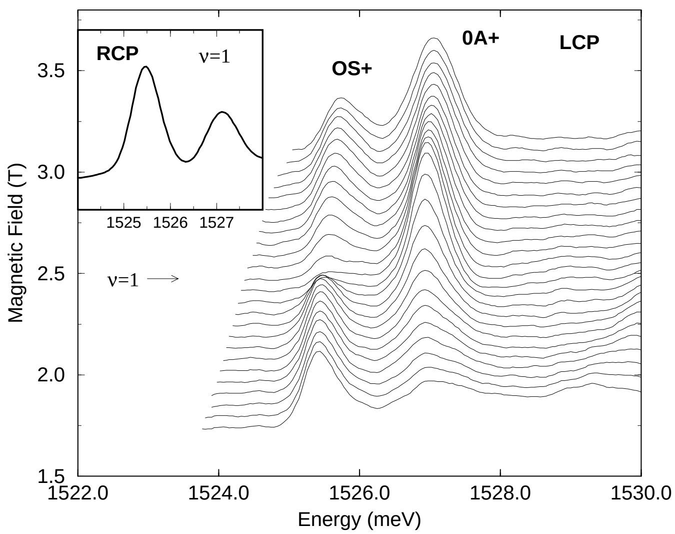

FIG. 2. Low-energy absorption in LCP at T=0.53K of sample A. The transition labeled 0S+ monitors absorption into the symmetric-state of the LLL while 0A+ corresponds to absorption into the antisymmetric state. Note the strong quenching of the lowest energy transition exactly at $\nu = 1$. The inset displays the absorption in RCP at $\nu = 1$. The significantly different behavior observed in RCP indicates that the selection rules are active.

Figure 1 displays the relevant inter-band transitions and polarization selection rules in the vicinity of $\nu = 1$. Also shown is a reproduction of the phase diagram constructed by Murphy *et al.* [14] and discussed in the introduction. Optical selection rules [6,8] dictate that the lowest-energy transition in the left-circular polarization (LCP) of the light field will monitor absorption into the symmetric spin-up state of the LLL around $\nu = 1$. Figure 2 displays the LCP spectra in the vicinity of $\nu = 1$ for sample A at a temperature T=0.53K. The inset displays the absorption at $\nu = 1$ in RCP and highlights the distinctly different behavior observed in the two polarizations. The ratio of 20:1 in absorption between RCP and LCP at 1525.5 meV indicates that the optical selection rules shown in Fig. 1 are active. A tunneling gap of $\Delta_{SAS} = 0.7$meV puts sample A into a regime where the gap at $\nu = 1$ should be largely a single-particle effect and the ground-state at $\nu = 1$ should be nearly fully pseudospin polarized along $\hat{x}$, i.e. the ground-state at $\nu = 1$ consists of a fully occupied symmetric state of the LLL.

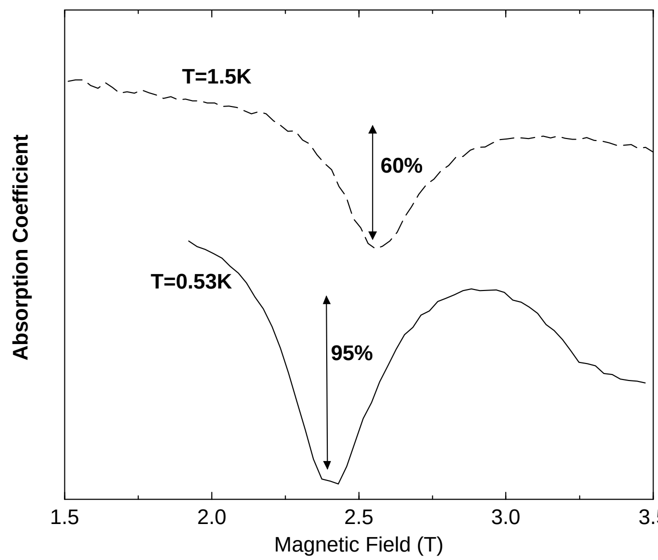

FIG. 3. Quenching of absorption into the symmetric state of the LLL as the Fermi level moves through $\nu = 1$ at T=1.5K and T=0.53K for sample A. Note that the quenching is well developed at T=1.5K. The quenching at $\nu = 1$ is measured relative to the absorption level at 2T and 3T.

In the region of $\nu = 1$ we observe two low-energy transitions whose final states we assign to the symmetric spin-up ($0S+$) and antisymmetric spin-up ($0A+$) states of the LLL. The most striking feature in Fig.2 is the strong quenching of the lowest-energy transition in LCP as the Fermi level passes through $\nu = 1$. This behavior is very reminiscent of the quenching seen in the single-layer system at $\nu = 1$ where the ground-state is fully *spin* polarized and skyrmions are present for small deviations from $\nu = 1$ [6,8]. The quenching of the lowest-energy LCP transition is an optical *signature* of a ferromagnetically aligned ground-state in the single-layer system. The observed minimum of the absorption in the DQW structure shows that the lowest-energy transition in LCP is sensitive to the ground-state occupation of the symmetric level at $\nu = 1$. Figure 3 displays the magnetic field dependence of this absorption minimum as the Fermi level moves through $\nu = 1$ at two different temperatures. It is clear that the absorption minimum is already well-developed by T=1.5K and that below T=1.5K there are no qualitative changes in the absorption. All small intensity variations of the low-energy transitions have a monotonic temperature dependence indicating activated behavior. This is strong indication that there are no unoccupied symmetric states of the LLL exactly at $\nu = 1$ at zero temperature. Indeed, the observed spectral features are consistent with the expectation of a fully pseudospin polarized ground-state at $\nu = 1$ for sample A in the regime of relatively strong tunneling.

Qualitatively different behavior is observed in sample B. Sample B possesses a much smaller single-particle tun-

neling gap, $\Delta_{SAS} = 0.4$meV. Figure 4 shows an intensity map of the absorption for sample B in LCP at T=1.5K. At low fields ($B \leq 1.3T$, and $\nu \geq 4$) the absorption has excitonic character. Nevertheless, even in the low field regime the absorption clearly responds the the presence of the incompressible quantum Hall states of the 2D electron system. Intensity maxima and/or minima are present at filling factors $\nu = 8$, 6, 4 and 2. In addition to showing optical sensitivity to the position of the Fermi level, the optical anomalies allow for an accurate determination of the electron density. As in sample A, the spectra in sample B show strong polarization dependence. At fields corresponding to $\nu \leq 3$, the absorption develops a linear field dependence indicative of well-developed Landau level-like transitions.

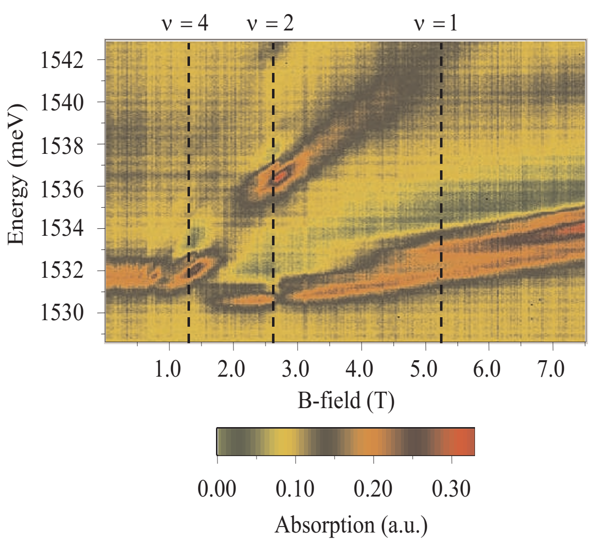

FIG. 4. Intensity plot of the absorption in LCP for sample B at T=1.5K. The positions of several filling factors are displayed. Note, in sharp contrast to sample A, the lack of quenching of the lowest-energy transition at $\nu = 1$.

For sample B in the region of $\nu = 1$, the response of the lowest-energy transition in LCP is strikingly different than that seen in sample A. Rather than observing a quenching of the absorption, the lowest-energy LCP transition displays a weak maximum as the Fermi level is swept through $\nu = 1$ at T=0.5K. The observed lack of an optical anomaly in sample B implies the existence of a finite density of available states in the symmetric state of the LLL at $\nu = 1$. The observation of non-zero absorption persists to the lowest accessible temperature of T=0.5K. These observations suggest that the ground-state at $\nu = 1$ in sample B is not fully pseudospin polarized along the $\hat{x}$ direction.

Another indication of a drastically different ground-state in sample B comes from an examination of the temperature dependence of the absorption at $\nu = 1$. Figure 5 displays individual spectra at $\nu = 1$ taken at various temperatures. In sharp contrast to sample A, the absorption in sample B changes dramatically as the temperature is reduced from T=2K to T=1K. Interestingly, the absorption into the lowest-energy LCP transition actually *increases* at low temperatures, indicating that our observations are not limited by the thermal population of excited states. Below T=0.8K the spectral changes stabilize and indicate activated behavior. Such unusual temperature dependence has been observed in transport as a deviation from simple activated behavior at relatively low temperatures ($T \leq 0.5K$), despite the presence of a measured gap that exceeds this temperature by a factor of 20 [14]. Theoretically this behavior has been associated with a thermally induced collapse of the order that produced the collective gap [13].

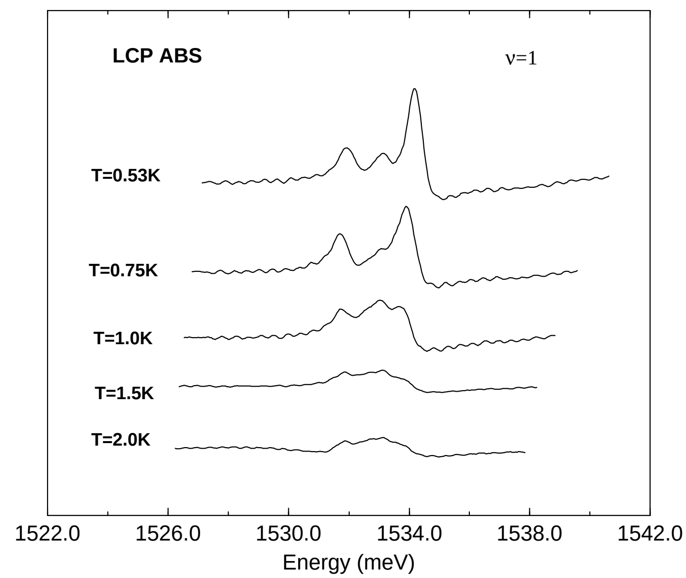

FIG. 5. Individual absorption spectra in LCP at $\nu = 1$ for sample B taken at various temperatures. The spectra change dramatically between 2K and 1K, suggesting a rapidly evolving ground-state. Below T=0.8K the lowest-energy transitions appear activated.

Incomplete pseudospin polarization of the ground-state at $\nu = 1$ in these systems is due to the reduction in symmetry from $SU(2)$ to $U(1)$ caused by the inter-layer Coulomb interactions and has been anticipated theoretically [10–13]. The symmetry-breaking term of the inter-layer Coulomb interaction does not commute with the total pseudospin operator, $[V_{sb}, S] \neq 0$, introducing quantum fluctuations, and making total pseudospin no longer a sharp quantum number [13].

It is important to note that the incompletely pseudospin polarized state remains incompressible and exhibits a gap for both neutral and charged elementary excitations. As a consequence, a well-defined $\nu = 1$ quantum Hall state is observed in transport in sample B.

For a non-interacting model, partial pseudospin polarization would be incompatible with a quantum Hall plateau. Thus the observed spectra represent a non-trivial manifestation of inter-layer coherence.

In conclusion, we have presented magneto-absorption data from the coupled DQW structure in the quantum Hall regime around $\nu = 1$ which reveal intriguing optical anomalies that have no analog in the single-layer system. Magneto-absorption appears to be sensitive to changes in the ground-state of the electron system in a manner inaccessible to transport. Finally, low-temperature spectra obtained from a sample with a relatively small tunneling gap, $\Delta_{SAS} = 0.4$meV, suggest that this ground-state at $\nu = 1$ is not fully pseudospin polarized. The observed absorption is consistent with the presence of quantum fluctuations caused by the reduction in the symmetry of the Coulomb interactions. Further optical experiments are underway to explore more of this rich phase diagram.

We acknowledge valuable conversations with Allan MacDonald, David Broido, and Luis Brey. The work completed at Boston University was supported by the NSF under grant number DMR 9701958.

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